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AN OBSERVATIONAL ANALYSIS OF THE ZONAL WIND FIELDS OF SHARPLY RECURVING, SLOWLY RECURVING AND NON-RECURVING CYCLONES

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1. INTRODUCTION

Environmental wind fields of recurving and non-recurving tropical cyclones were examined to: 1) observe how the wind fields associated with non-recurving cyclones differ from those with recurving cyclones prior to beginning recurvature and; 2) observe how synoptic scale wind fields interact with the circulation of recurving cyclones 1 to 3 days prior to the beginning of recurvature.

2. METHODOLOGY

Rawinsonde data for a total of 87 recurving cyclones and 85 non-recurving cyclones which transversed in the Northwest Pacific during the years 1957-77 were analyzed using data sets previously developed by W. M. Gray. Recurring cyclones were grouped into two categories; cyclones which undergo recurvature shortly after beginning recurvature (63 Sharply Recurring cyclones) and cyclones which gradually turn to the right after beginning recurvature (24 Slowly Recurring cyclones). The term "beginning of recurvature point", or R point, will be used to indicate the location where recurving cyclones first begin to deviate to the right from their previous west-northwest track. The non-recurving cyclone data set includes cyclones which moved west throughout their lifetimes.

In order to observe how the environmental wind fields associated with sharply and slowly recurving cyclones change with time as the recurving cyclones approach, and then pass, the beginning of recurvature point, the cyclone tracks of the sharply recurving and slowly recurving cyclones were divided into multiple 24 hour time periods as shown in Fig. 1.

3. DISCUSSION

It was found that the largest wind field differences between non-recurving cyclones and recurving cyclones, immediately prior to beginning recurvature, occurred in the zonal component for areas 6° and 8° to the north (octant 1), northwest (octant 2) and west (octant 3) of the cyclone's center. (The "octant" configuration used in this analysis is illustrated in Fig. 2). Environmental wind field differences on the equatorward side of the cyclone were found to be negligible. Based on these results, the zonal wind field 6° and 8° to the north, northwest and west of the recurving and non-recurving cyclone data sets are discussed below.

3.1 Non-recurving Cyclones

Figures 2 and 3 show zonal wind profiles at 6° and 8° respectively for the three non-recurving time periods (defined in Fig. 1) in octants 1, 2 and 3. The 6° zonal wind profiles (Fig. 2) in all three octants for all three non-recurving (NR) time periods are from an easterly component throughout the

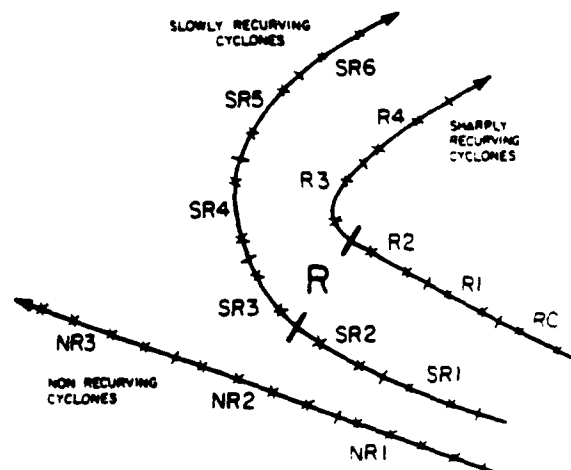


Figure 1: The sharply recurving and slowly recurving cyclone tracks divided into consecutive 24 hour time periods. The non-recurving cyclone tracks were divided into three equal time periods which lasted 50 hours on average. The large letter "R" marks the location where the recurving cyclones begin deviating from their previous west-northwest course. The small x's along the cyclone tracks represent the time (00 and 12 UTC) when rawinsonde data was collected from the surrounding northwest Pacific rawinsonde network.

troposphere, except in octant 1, where the zonal winds in the upper troposphere are from a weak westerly component. The 8° zonal profiles (Fig. 3) in octant 1 for periods NR1 and NR2 are negative whereas positive zonal winds have penetrated into the mid and upper troposphere in NR3. The zonal wind profiles in octant 2 also show that weak positive zonal winds have penetrated the 200 - 400 mb level at period NR3. However, the zonal profiles in octant 3 show that the zonal winds for all three non-recurving time periods are from an easterly component throughout the troposphere. Note that even though westerly winds penetrated the mid and upper troposphere at 8° to the north and northwest of the cyclone during NR3, the cyclone remained on a west-northwest course.

3.2 Sharply Recurring Cyclones

Figure 4 shows the zonal wind profiles at 6° for the five sharply recurring time periods (R0-R4) in octants 1, 2 and 3. Prior to the beginning of sharp recurvature, periods R0, R1 and R2, the 6° zonal wind profiles in octants 1 and 2 show zonal winds from an easterly component in the mid and lower troposphere and from a weak westerly component in the upper troposphere. Zonal winds in octant 3 are from an easterly component at all levels of the troposphere. Throughout R0,

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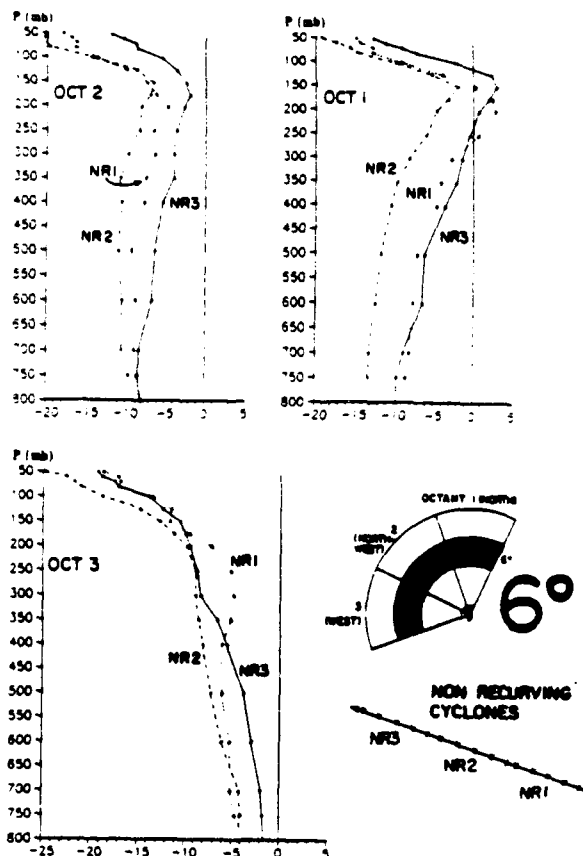


Figure 2: The 6° zonal wind profiles for the three non-recurring time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1} .

R1, and R2 the zonal profiles of the sharply recurving cyclones prior to beginning recurvature are similar to the profiles for non-recurring cyclones (Fig. 2) except for the positive zonal winds in the upper troposphere in octants 1 and 2. Since these relatively weak positive zonal winds occur during all three time periods prior to sharp recurvature, they are likely the result of seasonal climatology. It should be noted, most of the cyclones which recurved sharply, did so during the months of September, October and November. During these months, the mid-latitude westerlies migrate equatorward. Conversely, most of the non-recurring cyclones developed during the months of July, August and September.

The results in Fig. 4 also show that significant changes in the zonal wind fields have taken place in all three octants by period R3. During the previous three time periods (when the cyclones were moving west-northwest) zonal winds in the mid and upper troposphere were from an easterly or weak westerly component in all three octants. As the cyclones begin to recurve sharply during period R3, positive upper tropospheric zonal winds in octant 1 increase in speed and penetrate down into the mid-troposphere. In octant 2, positive zonal winds penetrate down to near the 700 mb level. Zonal wind differences between periods R2 and R3 in this octant are greater than $20 ms^{-1}$ at the 300 mb level. In octant 3, the zonal winds become positive throughout the troposphere.

The 8° zonal profiles for the five sharply recurring time periods are shown in Fig. 5. The zonal profiles in octants 1 and 2 for R0 and R1 show zonal winds from an easterly component in the mid and lower troposphere and from a weak westerly component in the upper troposphere. Note that the profiles at this radius for these two periods have characteristics similar to the non-recurring profiles (Fig. 3). The significant changes which occur at period R2 are similar to the changes

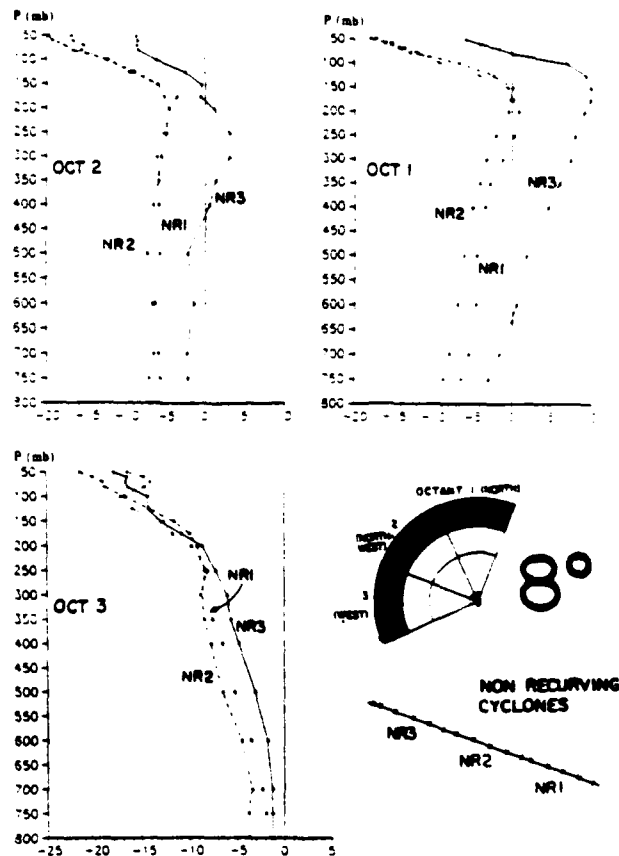


Figure 3: The 8° zonal wind profiles for the three non-recurring time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1} .

which occurred between periods R2 and R3 at 6° where in the mid and upper tropospheric zonal winds in octants 1 and 2 at 8° shifted from an easterly component to westerly component between periods R1 and R2. The important aspect of this change is that even though the zonal component of the wind at period R2 is in excess of $10 ms^{-1}$ in the mid and upper troposphere at 8° radius, the cyclone did not change direction.

3.3 Slowly Recurring Cyclones

Figures 6 and 7 show the zonal wind profiles at 6° and 8° for the six slowly recurring time periods (SR1-SR6) in octants 1, 2 and 3. Prior to the beginning of slow recurvature (periods SR1 and SR2) zonal profiles at 6° in octants 1, 2 and 3 show winds from an easterly component throughout the troposphere. As the cyclones begin slow recurvature (during period SR3), zonal winds in the mid and upper troposphere in octant 2 and mid-troposphere in octant 3 shift from an easterly component to a weak westerly component. Zonal winds in octant 1 remain negative at nearly all tropospheric levels. As the cyclones continue to recurve during periods SR4, SR5 and SR6, zonal winds in the mid and upper troposphere in all 3 octants become positive and gradually increase in speed.

Zonal profiles at 8° for periods SR1-SR6 are shown in Fig. 7. Zonal profiles at SR1 are from an easterly component throughout the troposphere in both octants 1 and 2. At period SR2, zonal winds in octants 1 and 3 are still from an easterly component throughout a majority of the troposphere while the zonal winds in octant 2 have become neutral throughout the troposphere. As the cyclones slowly begin to recurve during period SR3, zonal winds in the mid and upper troposphere in octants 1 and 2 shift to a westerly component as do mid-

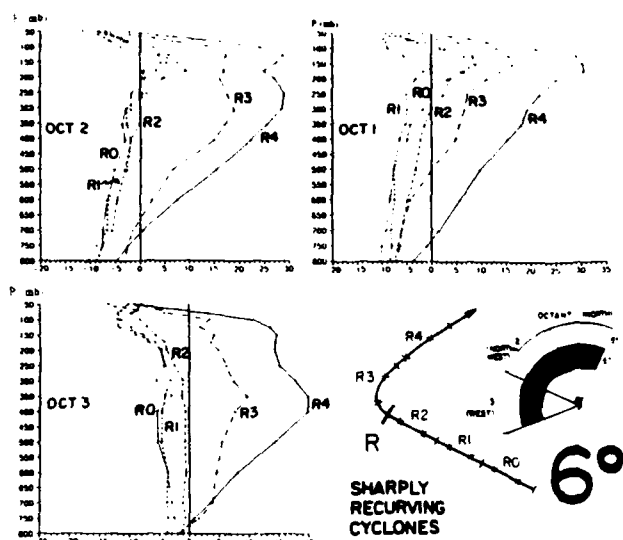


Figure 4: The 6° zonal wind profiles for the five sharply recurring time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1} .

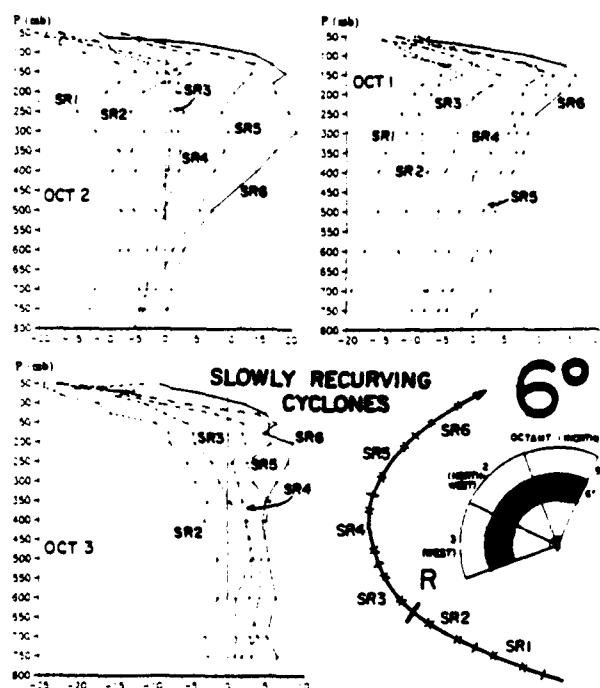


Figure 6: The 6° zonal wind profiles for the six slow recurring time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1} .

tropospheric zonal winds in octant 3. As the cyclones continue to recurve to the north and northeast during the remaining three time periods, zonal winds throughout the troposphere in all three octants become positive and gradually increase in speed.

4. RESULTS

Environmental wind fields at 6° and 8° north, northwest and west of cyclones are important for distinguishing the likely beginning recurvature from continued west-northwest motion.

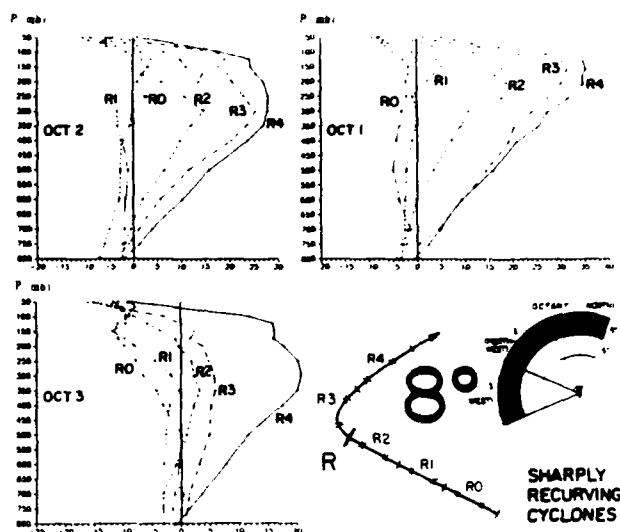


Figure 5: The 8° zonal wind profiles for the five sharply recurring time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1} .

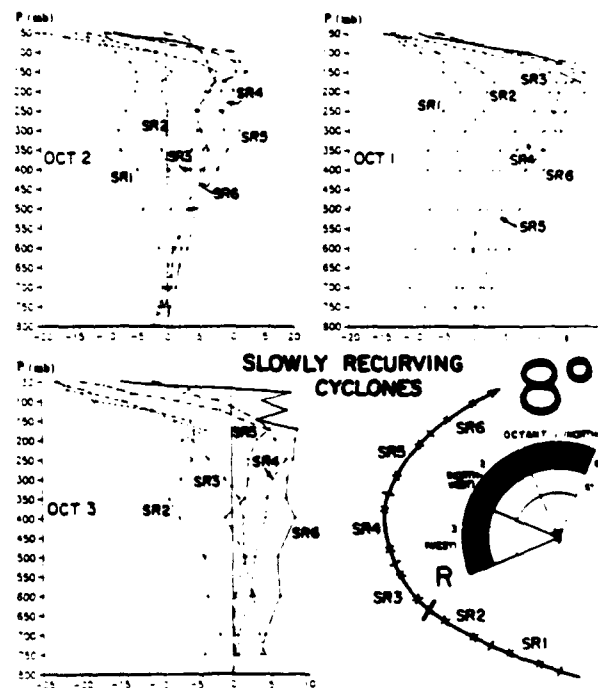


Figure 7: The 8° zonal wind profiles for the six slow recurring time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units in ms^{-1} .

Sharply recurring cyclones were not observed to begin recurvature until positive zonal winds in the mid and upper troposphere to the north, northwest and west of the cyclone penetrated to within 6° of the cyclone center. The slowly recurring cyclones did not begin to recurve until positive zonal wind penetrated the mid and upper troposphere at radius 6° northwest of the cyclone, and the mid troposphere at 6° west of the cyclone. The cyclones which did not recurve remained embedded in easterly flow at 6° north, northwest and west of the cyclone's center.

It was also shown that the zonal wind fields 8° north and northwest of the cyclone could change significantly and have no effect on changing the direction of the cyclone. However, this does not imply that the wind fields at 8° from the cyclone are not significant. Zonal wind fields 8° from the cyclones' center did change significantly 12-24 hours prior to sharp recurvature (period R2). Before this time (periods R0 and R1), the winds profiles were similar to non-recurving cyclones. This suggests that for recurvature to occur in the immediate future, zonal wind fields in the mid and upper troposphere 8° from the cyclone's center must shift to a positive component or become neutral (as in the case of slowly recurving cyclones).

5. FORECASTING CYCLONE RECURVATURE USING 500 AND 200 MB WINDS

It was shown when positive zonal winds in the mid and upper troposphere penetrate within 6° of the cyclone, cyclones begin to recurve. It was also shown that when positive zonal winds penetrate to within 8°, the cyclones may begin to recurve in the near future. For this reason, a recurvature forecasting scheme was developed based on the mid (500 mb) and upper (200 mb) tropospheric wind fields to the north, northwest and west of the cyclone.

A "recurvature number", or RECNUM value, is defined as the average speed and direction of the zonal winds at the 200 and 500 mb levels at 6 and 8° to the north, northwest and west of the cyclone. Meridional winds at 200 mb, north and northwest of the cyclone,¹ are also used for the RECNUM calculation which in mathematical form is given by:

$$\frac{\sum (u_{200} + u_{500})}{2} \text{ 200mb} + \frac{\sum (u_{200} + u_{500})}{2} \text{ 500mb} + \frac{\sum (v_{200} + v_{500})}{2} \text{ 200mb}$$

1 = Oct 1 1 = Oct 1 1 = Oct 1

Figure 8 shows RECNUM values for sharply recurving, slow recurving, left turning and non-recurving time periods defined in this study. In general, when the cyclones are moving on a westerly course the RECNUM values are typically negative; when the cyclones are moving north or northeast the RECNUM values are positive. Sharply recurving cyclones exhibited recurvature numbers which increased rapidly as the cyclones were recurving whereas the RECNUM values increased only gradually as slowly recurving cyclones were recurving. The non-recurving cyclones had varying though negative RECNUM values during all three time periods.

To test if the recurvature numbers were of value for predicting recurvature, RECNUM values were calculated for 55 tropical cyclones which developed during the 1984, 1985 and part of the 1986 Northwest Pacific tropical cyclone seasons. The wind field data needed to calculate the recurvature numbers were acquired from the Bureau of Meteorology Research Centre (BMRC).

Results of this test showed that the recurvature numbers relate fairly well to tropical cyclone direction. As seen in Fig. 9, 42% of the cyclone direction variance can be explained by measurements of the 500 and 200 mb wind fields to the north, northwest, and west of the cyclone.

To see if the recurvature numbers could predict tropical cyclone direction on a real time basis, the RECNUM forecasting scheme was employed during the Tropical Cyclone Motion experiment (TCM-90) which was conducted on the island of Guam during the summer of 1990 (Elsberry, 1990). During this experiment, recurvature numbers were calculated for each point on a 2.5° latitude/longitude grid, extending from 100°E to 160°E and 5°N to 35°N. Tropical cyclone motions were forecasted in the following way. The position (latitude/longitude) of the cyclone at $t = 0$ was found on the RECNUM direction analysis grid. The cyclone was then advected based on this RECNUM direction for the first 24 hours (The speed of the

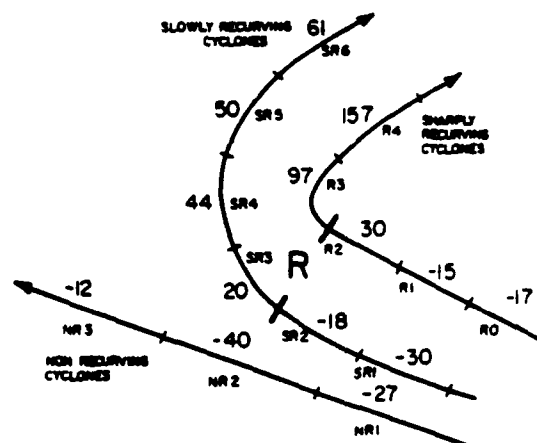


Figure 8: RECNUM values for the sharply recurving, slowly recurving and non-recurving cyclone time periods.

Recnum vs. Cyclone Direction

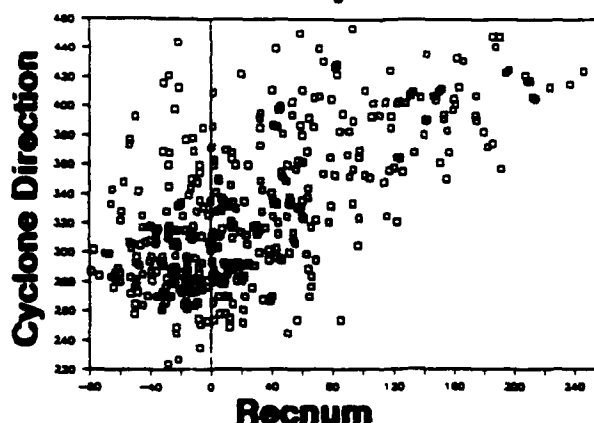


Figure 9: Scatter diagrams showing how the RECNUM value relates to tropical cyclone direction (Note: The direction values plotted on the ordinate which are greater than 360 represent motion east of due north; example "400" = 400-360 or 040 degrees).

cyclones was usually based on persistence and/or climatology). The location of the cyclone at the end of the first 24 hour time period was then found on the 24 h RECNUM/direction grid and a new direction was found and the cyclone was advected in this new direction for the next 24 hours. This procedure was then repeated to estimate the location of the cyclone at 48 and 72 hours after the initial forecast time.

Figure 10 shows two of the cyclones for which recurvature numbers were used to forecast motion. The first, tropical cyclone Yancy, moved on a generally west-northwest course throughout most of its' lifetime, except when it was east of Taiwan. During this time, a mid latitude trough moved to the north of the cyclone and it was uncertain if the cyclone would recurve or would move back to the west-northwest. The RECNUM forecast made at 08/18/0000z indicated the cyclone would move on a west-northwest course during each of the three 24 forecast time periods. Although the cyclone did turn towards the north-northwest during the first 24 hour time period, it resumed a west-northwest course during the second and third forecast periods.

Tropical cyclone Zola had two significant track deviations in its lifetime. The first occurred at 18/1800z when the cyclone turned sharply back towards the northwest from its prior northeast course. The RECNUM forecast made 18 hour

¹The meridional wind field helped to identify sharp recurvature from slow recurvature after the cyclones had begun to recurve.

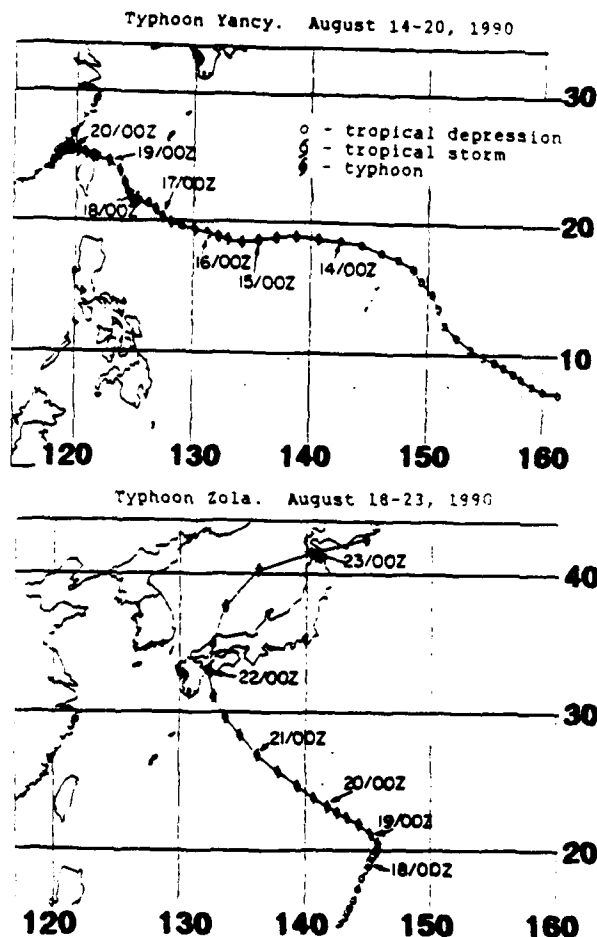


Figure 10: Working best tracks of Typhoon Yancy (top) and Zola (bottom).

earlier (18/0000z, see Fig. 11) anticipated this track change. The second track deviation occurred when the cyclone actually underwent recurvature on 22/0000z, over Southern Japan. The RECNUM forecasts made 19/0000z and 20/0000z correctly forecast the recurvature event to occur.

5.1 Summary of TCM-90 RECNUM Forecast

The recurvature number forecast technique showed considerable promise for both storm cases. The RECNUM forecast for Yancy to move west-northwest while it was still east of Taiwan was beneficial, even though the cyclone moved on a north-northwest course during the initial 24 hour forecast period. The RECNUM forecast would benefit the forecaster in this case by making him aware that the environment to the northwest of the cyclone was not favorable for recurvature and that any change of course was only likely to be for a short time.

The RECNUM forecast of the two Zola track deviations was very favorable. The recurvature forecast for the first deviation showed that as the recurvature numbers to the poleward side of the cyclone decreased with time, the cyclone would turn to the left and resume a west-northwest course. The second track deviation was also predicted correctly. The RECNUM forecast showed that as the recurvature numbers to the north of Zola increased with time, the likelihood of the cyclone recurving off to the northeast also increased.

6. CONCLUSIONS

It is apparent that the zonal wind fields in the mid and upper troposphere at 6° and 8° radius from the center of trop-

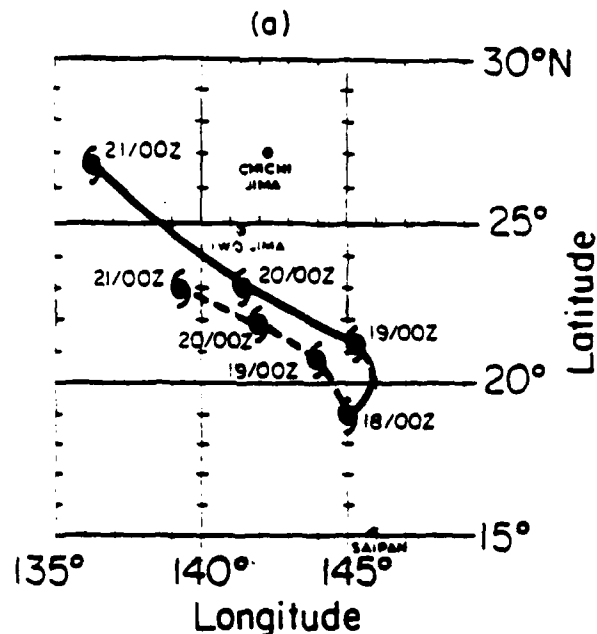


Figure 11: RECNUM forecast made 18 Aug. 0000z (dashed line) and actual working best track (solid line) of Typhoon Zola.

ical cyclones are important for distinguishing west-northwest motion from beginning recurvature. As discussed in section 4, both sharply recurving and slowly recurving cyclones do not begin to recur until positive zonal winds penetrate to within 6° on the northwest side of the cyclone center. Cyclones were typically 12-24 hours from recurvature when the zonal winds at 8° to the northwest of the cyclone center became neutral or shifted to a westerly component.

The results of the recurvature number forecasting scheme are promising. It is recommended that this scheme should be deployed at tropical cyclone forecast centers to be used as guidance to forecasters during critical recurvature/non-recurvature situations. A word of caution however is that the recurvature number forecast scheme is based on analysis data (which are typically poor over the tropics, especially in the mid-troposphere) and prognostic fields. When the data which go into a forecast are poor, the recurvature number forecast are likely to be no better. Clearly, the best way to accurately measure wind fields at critical levels (~300-400 mb) is to fly reconnaissance aircraft at 6° to 8° to the northwest of the cyclone and measure the wind fields directly.

Our next goal here at Colorado State University is to analyze the wind field data gathered from the TCM-90 experiment and use it to verify how well individual case data relates to the recurvature composite analysis results.

7. ACKNOWLEDGMENTS

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